

# Chargino production via $Z^0$ -Boson Decay in a Strong Electromagnetic Field

A.V.Kurilin\*

Moscow Technological Institute<sup>†</sup>,  
Leninsky Prospect, 38a, Moscow, 119334, Russia

February 11, 2015

## Abstract

In the framework of MSSM the probability of  $Z^0$ -boson decay to charginos in a strong electromagnetic field,  $Z^0 \rightarrow \chi^+ \chi^-$ , is analyzed. The method of calculations employs exact solutions of relativistic wave equations for charginos in a crossed electromagnetic field. Analytic expression for the decay width  $\Gamma(Z^0 \rightarrow \chi^+ \chi^-)$  is obtained at an arbitrary value of the parameter  $\varkappa = em_Z^{-3} \sqrt{-(F_{\mu\nu} q^\nu)^2}$ , which characterizes the external-field strength  $F_{\mu\nu}$  and  $Z^0$ -boson momentum  $q^\nu$ . The process  $Z^0 \rightarrow \chi^+ \chi^-$  is forbidden in vacuum for the case of relatively heavy charginos:  $M_{\chi^\pm} > m_Z/2$ . However in an intense electromagnetic background this reaction could take place in the region of superstrong fields ( $\varkappa > 1$ ).

---

\*E-mail address: kurilin@mail.ru

<sup>†</sup>on leave from Moscow State Open Pedagogical University

Minimal Supersymmetric extension of the Standard Model (MSSM) [1] is a neat solution of the famous hierarchy problem [2] and it predicts a number of new particles to be discovered. In this large family of hypothetical "superparticles" there are charginos  $\chi_1^\pm, \chi_2^\pm$  which arise as a mixture of winos  $\tilde{W}^\pm$ , the spin-1/2 superpartners of the gauge  $W^\pm$  bosons, and higgsinos  $\tilde{H}^\pm$ , the fermion superpartners of the two scalar Higgs fields which break spontaneously the electroweak symmetry. Vacuum expectation values  $v_1, v_2$  of the two Higgs fields can be characterized by the angle  $\beta$  which is defined as usual by the ratio:  $\tan \beta = v_2/v_1$ . Chargino masses can be expressed in terms of the fundamental supersymmetry (SUSY) parameters  $M_2$  and  $\mu$ :

$$M_{\chi_{1,2}}^2 = \frac{1}{2} (\mu^2 + M_2^2 + 2m_W^2 \mp \Delta), \quad (1)$$

where  $m_W$  is the  $W$ -boson mass and the quantity  $\Delta$  determines the difference between the squares of chargino masses ( $M_{\chi_2} > M_{\chi_1}$ ):

$$\Delta = M_{\chi_2}^2 - M_{\chi_1}^2 = \left[ (\mu^2 + M_2^2 + 2m_W^2)^2 - 4(\mu M_2 - m_W^2 \sin 2\beta)^2 \right]^{1/2}. \quad (2)$$

For the sake of simplicity in present calculations it is assumed that the Higgs mass parameter  $\mu$  and the  $SU(2)$  gaugino masses  $M_2$  arising in the Lagrangian of MSSM with other soft SUSY-breaking terms are real.

In the leading order of perturbation theory the matrix element of  $Z^0$ -boson decay to a pair of the lighter charginos,  $\chi_1^\pm$ , is given by

$$S_{fi} = i \int d^4x \bar{\chi}_1(x, p) \gamma^\mu (g_{V1} + \gamma^5 g_{A1}) \chi_1^c(x, p') Z_\mu(x, q), \quad (3)$$

where the vertex of  $Z^0$ -boson and  $\chi_1^\pm$ -chargino couplings can be described by the two constants:

$$g_{V1} = \frac{g}{8 \cos \theta_W} (2 - 8 \cos^2 \theta_W - \cos 2\phi_R - \cos 2\phi_L) \quad (4)$$

$$g_{A1} = \frac{g}{8 \cos \theta_W} (\cos 2\phi_R - \cos 2\phi_L) \quad (5)$$

The two angles  $\phi_R$  and  $\phi_L$  define the relationship between charginos, winos and higgsinos and can be computed from the formulae:

$$\cos 2\phi_R = \frac{\mu^2 - M_2^2 - 2m_W^2 \cos 2\beta}{\Delta}, \quad (6)$$

$$\cos 2\phi_L = \frac{\mu^2 - M_2^2 + 2m_W^2 \cos 2\beta}{\Delta}, \quad (7)$$

whereas the Weinberg angle  $\theta_W$  determines the usual relationship between  $W$ -boson and  $Z$ -boson masses:  $\cos \theta_W = m_W/m_Z$ .

The method of calculations in this paper is based on the crossed-field model, which was successfully applied in our previous investigations dealing with  $W^\pm$  and  $Z^0$ -bosons decays [3, 4] and with SUSY processes in background electromagnetic fields [5, 6]. The main idea of this approach is to describe interactions with an external electromagnetic background by choosing specific wave functions  $\chi^-(x, p)$  and  $\chi^+(x, p')$  for charginos  $\chi^\pm$  which are exact solutions of the Dirac equation in a crossed electromagnetic field. This method makes it possible to take into account the non-perturbative interactions with the electromagnetic background and to obtain results for new reactions which are forbidden in vacuum (for a review see, for example, [7] and references therein). The processes of chargino production via  $W^\pm$  and  $Z^0$ -bosons decays in vacuum have been considered by many authors [8]. However present experimental limits on chargino masses [9] evidence that the reaction  $Z^0 \rightarrow \chi^+ \chi^-$  is forbidden under usual conditions and it inspires us to study the impact of strong electromagnetic fields on the decays mentioned above. The wave functions for charginos in a background electromagnetic field have the simplest form for a crossed-field configuration, in which case the field-strength tensor  $F_{\mu\nu}$  obeys the conditions:

$$F_{\mu\nu} F^{\mu\nu} = F_{\mu\nu} \tilde{F}^{\mu\nu} = 0. \quad (8)$$

The explicit form of theses wave functions is rather cumbersome and it can be found, for example, in [4, 10]. Substituting the chargino wave functions into expression (3) for the  $S$ -matrix element and performing integration of  $|S_{fi}|^2$  over the phase space we obtain the probability of  $Z$ -boson decay into a pair of the lighter charginos  $\chi_1^\pm$ .

$$P(Z^0 \rightarrow \chi_1^+ \chi_1^-) = \frac{G_F m_Z^4 c_1 (1 + \delta_1)}{96 \sqrt{2} \pi^2 q_0} \int_0^1 du \left\{ \left[ 1 + (3\rho_1 - 1)\lambda_1 \right] \Phi_1(z_1) - \frac{2\kappa^{2/3}}{[u(1-u)]^{1/3}} \left[ 1 - 2u + 2u^2 + (1 - \rho_1)\lambda_1 \right] \Phi'(z_1) \right\}. \quad (9)$$

The probability of chargino production in a crossed electromagnetic field is expressed in terms of the Airy functions  $\Phi'(z)$  and  $\Phi_1(z)$  which have the well-known integral representations.

$$\Phi(z) = \int_0^\infty \cos \left( zt + \frac{t^3}{3} \right) dt, \quad \Phi_1(z) = \int_z^\infty \Phi(t) dt, \quad \Phi'(z) = \frac{d\Phi(z)}{dz}. \quad (10)$$

These functions depend on the argument

$$z_1 = \frac{\lambda_1 - u(1-u)}{[\kappa u(1-u)]^{2/3}}, \quad (11)$$

which characterizes the electromagnetic-field-strength  $F^{\mu\nu}$  and  $Z$ -boson momentum  $q_\nu$  through the following invariant parameter

$$\varkappa = \frac{e}{m_Z^3} \sqrt{-(F^{\mu\nu} q_\nu)^2}. \quad (12)$$

The other dimensionless parameters in expression (9)  $\lambda_1, \rho_1, \delta_1$  are associated with chargino masses (1) and the coupling constants (4),(5)

$$\lambda_1 = \left( \frac{M_{\chi_1}}{m_Z} \right)^2, \quad c_1 = (\cos 2\phi_R + \cos 2\phi_L + 8 \cos^2 \theta_W - 2)^2, \quad (13)$$

$$\rho_1 = \frac{1 - \delta_1}{1 + \delta_1}, \quad \delta_1 = \left( \frac{\cos 2\phi_R - \cos 2\phi_L}{\cos 2\phi_R + \cos 2\phi_L + 8 \cos^2 \theta_W - 2} \right)^2. \quad (14)$$

Let now consider asymptotic estimates of the  $Z$ -boson partial decay width  $\Gamma(Z^0 \rightarrow \chi_1^+ \chi_1^-)$  in a crossed electromagnetic field at various values of the parameter  $\varkappa$  (12). In the domain of relatively weak fields the  $Z^0$ -boson decay width into a pair of lighter charginos can be described by the formula:

$$\begin{aligned} \Gamma(Z^0 \rightarrow \chi_1^+ \chi_1^-) = G_F m_Z^3 & \frac{c_1(1 + \delta_1)\lambda_1(5\rho_1 + 1 + 8\lambda_1(1 - \rho_1))}{64\pi\sqrt{6}(4\lambda_1 - 1)\sqrt{8\lambda_1 + 1}} \times \\ & \times \varkappa \exp \left[ -\frac{(4\lambda_1 - 1)^{3/2}}{3\varkappa} \right]. \end{aligned} \quad (15)$$

We see that the decay rate is exponentially suppressed at weak fields which is typical for processes being forbidden in vacuum. For numerical calculations presented below we employ the following parameters:

$$\tan \beta = 5, \quad M_2 = 200 \text{ GeV}, \quad \mu = 250 \text{ GeV}.$$

This choice corresponds to chargino masses  $M_{\chi_1} = 158 \text{ GeV}$  and  $M_{\chi_2} = 301 \text{ GeV}$  which can be easily obtained from equations (1),(2). In the area of relatively small values of the field-strength parameter  $\varkappa$  the partial decay width  $\Gamma(Z^0 \rightarrow \chi_1^+ \chi_1^-)$  into lighter charginos grows monotonously reaching the value  $\Gamma_{\chi_1} \simeq 7 \text{ MeV}$  at  $\varkappa = 3$ . Exact results of calculations are displayed in Fig.1 for the region  $\varkappa \leq 3$  where the probability of  $Z^0$ -boson decay into a pair of heavier charginos  $Z^0 \rightarrow \chi_2^+ \chi_2^-$  is negligibly small because of the large mass differences between  $\chi_1^\pm$  and  $\chi_2^\pm$ . However in strong fields the  $Z^0$ -boson decays into heavier charginos  $\chi_2^\pm$  become sizable and should be taken into account.

The probability of decay  $Z^0 \rightarrow \chi_2^+ \chi_2^-$  can be obtained from equation (9) by formal substitutions:  $\lambda_1 \rightarrow \lambda_2, c_1 \rightarrow c_2, \rho_1 \rightarrow \rho_2, \delta_1 \rightarrow \delta_2$ , where

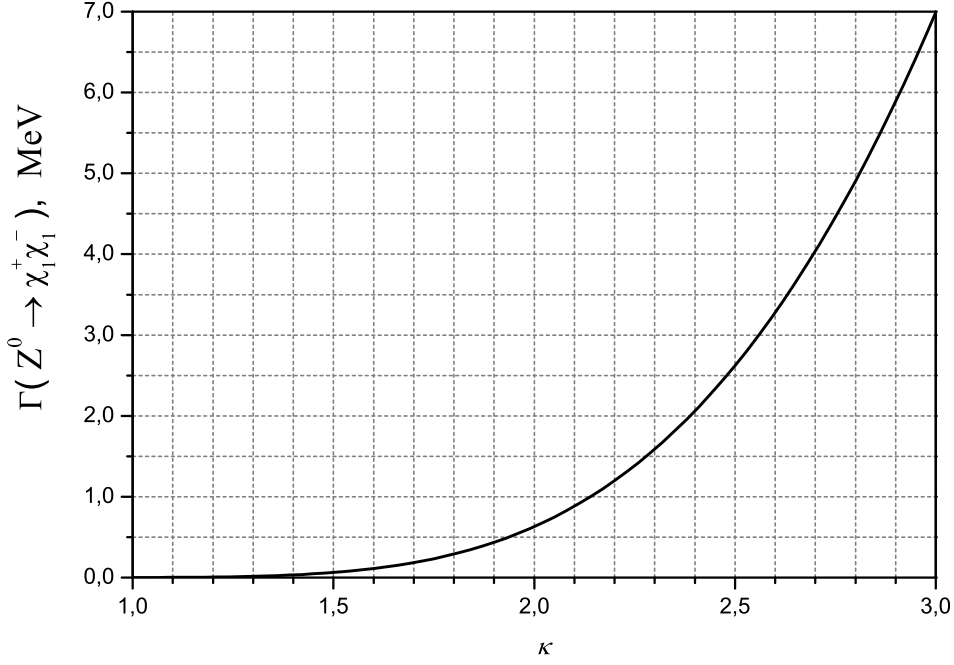


Figure 1: Partial decay width of  $Z^0$ -boson into lighter charginos at relatively weak fields plotted as a function of parameter  $\varkappa$  (12).

$$\lambda_2 = \left( \frac{M_{\chi_2}}{m_Z} \right)^2, \quad c_2 = (\cos 2\phi_R + \cos 2\phi_L - 8 \cos^2 \theta_W + 2)^2, \quad (16)$$

$$\rho_2 = \frac{1 - \delta_2}{1 + \delta_2}, \quad \delta_2 = \left( \frac{\cos 2\phi_R - \cos 2\phi_L}{\cos 2\phi_R + \cos 2\phi_L - 8 \cos^2 \theta_W + 2} \right)^2. \quad (17)$$

In the domain  $\varkappa \gg 10$  the partial decay widths of  $Z^0$ -boson into charginos  $\chi_i^\pm, i = 1, 2$  can be estimated by the the following equation:

$$\Gamma(Z^0 \rightarrow \chi_i^+ \chi_i^-) = G_F m_Z^3 \frac{c_i(1 + \delta_i)}{96\pi\sqrt{2}} \left[ \frac{15\Gamma^4(2/3)}{14\pi^2} (3\varkappa)^{2/3} + \frac{1}{3} + \frac{3\Gamma^4(1/3)}{110\pi^2} (3\varkappa)^{-2/3} + \frac{9\Gamma^4(2/3)}{104\pi^2} (3\varkappa)^{-4/3} \right]. \quad (18)$$

Now we can analyze chargino contribution to the total decay width of  $Z^0$ -boson in a background electromagnetic field. In Standard Model the  $Z^0$ -boson decay width  $\Gamma_Z$

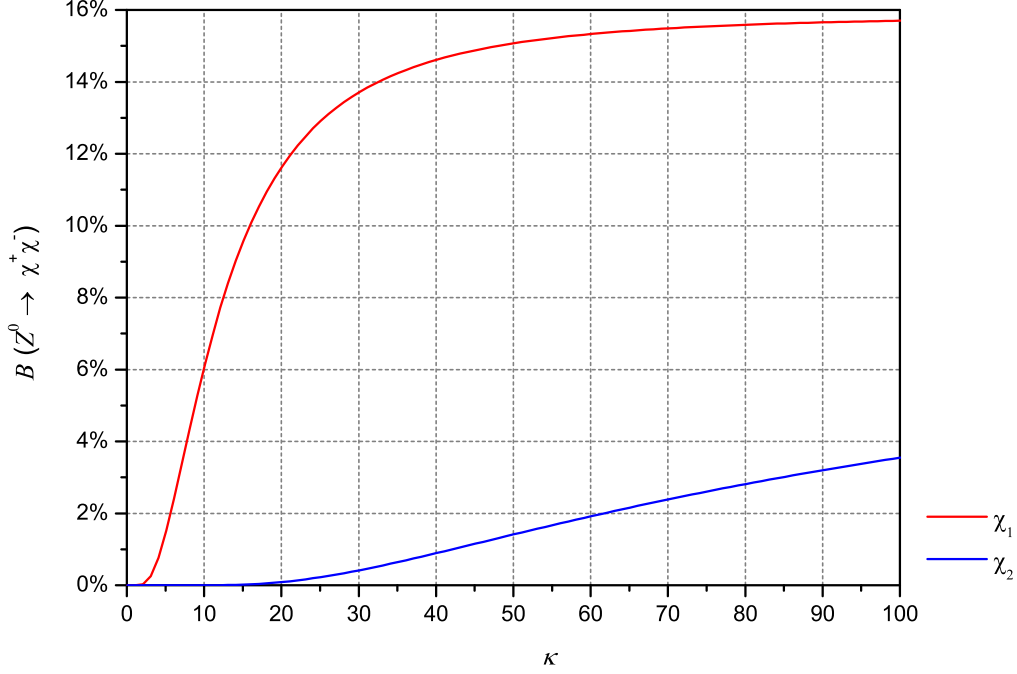


Figure 2: Branching ratios  $B(Z^0 \rightarrow \chi_i^+ \chi_i^-) = \Gamma(Z^0 \rightarrow \chi_i^+ \chi_i^-)/\Gamma_{\text{tot}}(\kappa)$  of  $Z$ -boson decays into charginos  $\chi_i^\pm, i = 1, 2$  in strong electromagnetic fields.

into quarks and leptons in a strong electromagnetic field depends on the background field-strength parameter  $\kappa$ :  $\Gamma_Z = \Gamma_{\text{tot}}(\kappa)$  and it was calculated in our paper [4]. Relying on these studies it is possible to obtain branching ratios of  $Z^0$ -boson decay into charginos  $B(Z^0 \rightarrow \chi_i^+ \chi_i^-) = \Gamma(Z^0 \rightarrow \chi_i^+ \chi_i^-)/\Gamma_{\text{tot}}(\kappa)$  in a background electromagnetic field. Numerical calculations based on equation (9) are presented in Fig. 2. We see that the processes of chargino production can be significant in strong fields and it can give a sizable contribution to the total decay width of  $Z^0$ -boson. In superstrong fields the branching ratio of decays into lighter charginos  $B(Z^0 \rightarrow \chi_1^+ \chi_1^-)$  is about 16% while the branching ratio of decays into heavier ones  $B(Z^0 \rightarrow \chi_2^+ \chi_2^-)$  can reach the values about 8%.

Thus summarizing the results obtained above we see that external electromagnetic fields can change drastically the physics of quantum processes in a vacuum and serve as a catalyst for new phenomena and new physics. As the external-field strength increases,

SUSY-decay modes of  $Z^0$ -boson could become observable and charginos  $\chi_i^\pm$  predicted in the framework of MSSM could be detected. Although external-field strengths necessary for direct observation of the processes  $Z^0 \rightarrow \chi_i^+ \chi_i^-$  are not yet available in experiments there are promising expectations to realize similar extreme conditions in high intensity laser interactions [11] or in physics of single crystals [12].

## References

- [1] H.P. Nilles, Phys. Rep. **110** (1984) 1;  
H. E. Haber and G. L. Kane, Phys. Rep. **117** (1985) 75;  
Stephen P. Martin, *A Supersymmetry Primer*, arXiv:hep-ph/9709356.
- [2] E. Witten, Nucl. Phys. **B188** (1981) 513;  
R.K. Kaul and P. Majumdar, Nucl. Phys. **B199** (1982) 36.
- [3] A.V. Kurilin, Yad. Fiz. **67** (2004) 2116 [Phys. At. Nucl. **67** (2004) 2095];  
arXiv:0709.0335 [hep-ph].
- [4] A.V. Kurilin, Yad. Fiz. **72** (2009) 1078 [Phys. At. Nucl. **72** (2009) 1034];  
arXiv:1309.2780 [hep-ph].
- [5] A.V. Kurilin, Phys. Lett. **B249** (1990) 455; Int. J. Mod. Phys. **A9** (1994) 4581;  
A.V. Kurilin and A.I. Ternov, Phys. Lett. **B381** (1996) 185.
- [6] A.V. Kurilin and A.I. Ternov, Yad. Fiz. **63** (2000) 1944 [Phys. At. Nucl. **63** (2000) 1855]; Pis'ma Zh. Eksp. Teor. Fiz. **63** (1996) 305 [JETP Lett. **63** (1996) 311];  
A.V. Kurilin, Yad. Fiz. **57** (1994) 1129 [Phys. At. Nucl. **57** (1994) 1066].
- [7] A.V. Borisov, A.S. Vshivtsev, V.Ch. Zhukovsky, and P.A. Eminov, Usp. Fiz. Nauk **167** (1997) 241 [Phys. Usp. **40** (1997) 229].
- [8] P. Fayet, Phys. Lett. **B125** (1983) 178; **B133** (1983) 363;  
S. Weinberg, Phys. Rev. Lett. **50** (1983) 387;  
J. Kalinowski, P.M. Zerwas, Phys. Lett. **B400** (1997) 112; arXiv:hep-ph/9702386.
- [9] K.A. Olive et al. (Particle Data Group) Chin. Phys. **C38** (2014) 090001.
- [10] A.V. Kurilin, Nuov. Cim. **112 A** (1999) 977; arXiv:hep-ph/0210194.
- [11] A.Di Piazza, C. Müller, K.Z. Hatsagortsyan, C.H. Keitel, Rev. Mod. Phys. **84** (2012) 1177; arXiv:1111.3886 [hep-ph];  
S.J. Müller, C.H. Keitel, C. Müller, Phys. Rev. **D90** (2014) 094008; arXiv:1408.2991 [hep-ph];
- [12] V.N. Baier, V.M. Katkov and V.M. Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals*, World Scientific Publishing Co, Singapore, 1998.